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Joining of dissimilar materials

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ABSTRACT

Emerging trends in manufacturing such as light weighting, increased performance and functionality increases the use of multi-material, hybrid structures and thus the need for joining of dissimilar materials. The properties of the different materials are jointly utilised to achieve product performance. The joining processes can, on the other hand be challenging due to the same different properties. This paper reviews and summarizes state of the art research in joining dissimilar materials. Current and emerging joining technologies are reviewed according to the mechanisms of joint formation, i.e.; mechanical, chemical, thermal, or hybrid processes. Methods for process selection are described and future challenges for research on joining dissimilar materials are summarized.

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1. Introduction

Among the many manufacturing technologies, joining has been identified as a key enabling technology to innovative and sustainable manufacturing [6]. Due to functional needs and technological limitations, it is usually not possible to manufacture a product without joining of some sort. Products are typically assembled using multiple components [100] and joining processes are essential in manufacturing to provide product function and increase manufacturing process efficiency. Improvements of material properties and traditional processes for monolithic structures as well as extended use of additive manufacturing processes can reduce the need for joining and the number of joints in a product [294]. Nevertheless, the production processes and the required functions of the products make a “joint-free” concept unrealistic in most cases. Moreover, the search for increased product features and performance from hybrid structures with different classes of materials requires the presence of joints. Understanding of joining technologies is therefore a key issue in manufacturing, and there is a continuous development of novel processes as well as improvements of existing processes.

Joining can be complex and spans a wide range of approaches, materials and techniques. Messler [149] defines joining to be: “The process used to bring separate parts of components together to produce a unified whole assembly or structural entity”. Campbell [44] considers joining as: “a large number of processes used to assemble individual parts into a larger, more complex component or assembly”. In [15,211] two definitions of joining are presented,

where the first definition is: “. . . joining is the act or process of putting or bringing things together to make them continuous or to form a unit”. The second definition explained in [15,211] is: “joining is the process of attaching one component or structural element to another to create an assembly”.

The Sub-Platform on Joining [6] of the EU Manufacture Technology platform defines joining as: “Creating a bond of some description between materials or components to achieve a specific physical performance”. This bond can take many forms, and can be described as being generated by one or a combination of several of the following processes:

- Mechanical—a joint formed through a mechanical mechanism,
- Chemical—a bond formed through chemical reaction,
- Thermal—a bond formed through applying thermal energy.

In this paper we will follow this definition, but add hybrid processes as a 4th class and divide thermal processes into fusion and solid-state processes.

1.1. Joining of dissimilar materials

The drive for more optimal, lightweight and high performance structures, and the trend of integrating an increased number of functions in each part [26] can be met by combining various materials into a multi-material hybrid structure. The different properties of the different materials are jointly utilised to achieve the product performance needed. This trend is reported for several industries such as: Automotive [176], Aeronautics [209,276], Clothing [289], Tooling [186], Implants [217], Power generation [131], and Marine application [22]. The mix of new materials will require a systematic approach to material selection: these materials will interact with each other in new ways, and new

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manufacturing systems might be needed [49]. This requires the ability to simultaneously optimize material choice and geometry. Recent developments include proposals for multi-material design procedures [276], and optimal material selection with respect to light weight and recyclability [209].

A commonly known example is the Boeing 787 Dreamliner which uses composite materials as the primary material in the airframe structure, although also includes 20% aluminium, 15% titanium, 10% steel, and 5% other [279]. In modern car body structures high strength steels can be used in the longitudinal beams for strength, aluminium alloys in bumper beams for lightweight and crashworthiness and composite sheets in panels for lightweight and high stiffness. The EU FP6-project SuperlightCar [223] showed how mass can be reduced by combining aluminium, steel, magnesium and glass fibre reinforced thermoplastics (see Fig. 1).

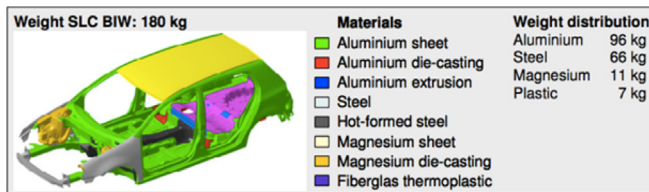


Fig. 1. Material distribution in a superlight car body [30].

Dissimilar materials can be described as: “materials or material combinations that are difficult to join, either because of their individual chemical compositions or because of large differences in physical properties between the two materials being joined” [44].

Hybrid structures can be defined as [12,221]: “A combination of two or more materials in a pre-determined configuration and scale, optimally serving a specific engineering purpose”. In this paper we will use the following definition for a hybrid structure: A hybrid structure consisting of two or more components of dissimilar materials joined together to achieve a specific physical performance.

These components of dissimilar materials are to be joined together, and different joining processes have unique strengths and limitations for the joining of dissimilar materials. There are, however, significant challenges when materials of different chemical, mechanical, thermal, or electrical properties are to be joined together. The incompatibility on chemical, thermal and physical levels (thermal expansion, ductility, fatigue/fracture mechanics, elastic modulus etc.) can create problems both for the joining process itself, but also for the structural integrity of the joints during the use phase of the product. Galvanic corrosion, different thermal expansion and other effects of bringing two different materials closely together must be addressed.

To be able to join dissimilar materials, the product design and the joining process design must equalize these challenges. As Messler [149] describes it: “differences must be minimized, inherently through the choice of material or through some other means. This becomes increasingly difficult as the basic nature – atomic level structure, microstructure, and (macrostructure) – of the various materials involved becomes more different.”

The field of joining is very large and there are a large number of different joining methods. This paper gives an overview of the state-of-the-art on a selection of processes. Many methods are not mentioned though, and joining of wood, glass and concrete/cement is not covered. The authors have a strong foothold in automotive industry, which to some extent explain the choice of methods described. The joining methods and the knowledge are still applicable for several industry sectors.

2. Review of joining methods for dissimilar materials

In this section, we review the joining process by the mechanisms of joint formation, e.g., mechanical, chemical and

thermal processes. Hybrid processes that combine one or two of the above methods are also reviewed.

2.1. Mechanical joining processes

2.1.1. Threaded fasteners

Joining using threaded fasteners or screws has been in practice for a long time. Screws of various forms can be applied in one-sided joining when access from the other side of the components is limited. Bolt and nut combinations are commonly used when access is available from both sides of the components to be joined. Fig. 2 shows some examples of threaded fasteners. When disassembly is required, threaded fasteners are usually the preferred method since unscrewing does not lead to destruction of the components. Screw joints for thin gauge sheet metals do not provide sufficient load bearing length of the screw, so other joining methods or additional elements, such as flow drill screws, collar forming, or spring nuts, are used to increase the load bearing length [71].

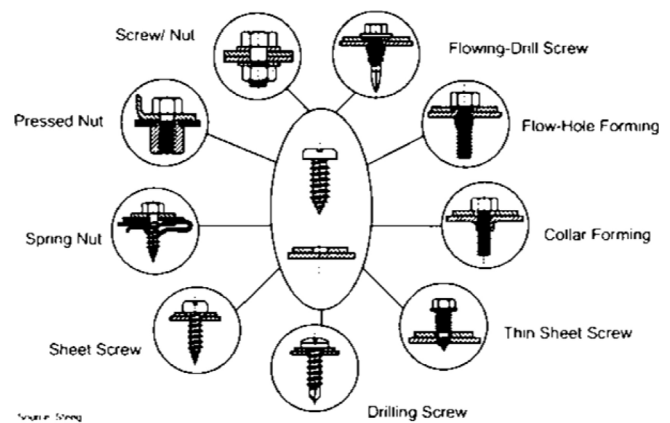


Fig. 2. Example of threaded fasteners [71].

Bolted joints have been in use for more than 500 years [33]. They are simple to use and virtually the only choice for disassembly and reassembly of a product, whether driven by maintenance or remanufacturing. Bolted joints can be designed for tensile or shear loads, or a combination. If the applied force is more or less parallel to the bolt, then the joint is called a tension or tensile joint (see Fig. 3).

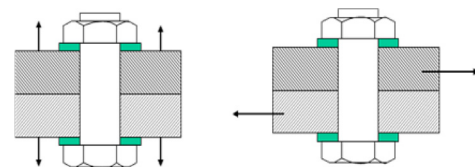


Fig. 3. Bolted joints in tension and shear.

If the applied force is perpendicular to the bolt axis, the joint is a shear joint. For other applications, a joint can be designed to withstand both tensile and shear loads. Bickford [33] provides an excellent overview of joint design, materials consideration, loading and strength analysis.

2.1.2. Flow drill screws

Flow Drill Screws, FDS, fill the void of a single-sided mechanical fastening method for structural automotive joints and at this point is a commercial off the shelf technology capable of both manual and fully automated assembly. The North American automotive industry is now following the trend set by European counterparts who have been using FDS since 1996 [43]. Traditional automotive steel-intensive Body In White (BIW) single-sided joining has been via gas metal arc welding. This fusion method implies however,

significant dimensional distortion and is less applicable to dissimilar material combinations. FDS can be used with or without a pre-drilled hole (depending on the screw). The rotating screw first heats up the material to facilitate penetration. As the screw tip penetrates the material, it also acts to extrude the material into a funnel shape. Once the tip has pierced the material, threads are formed and the screw is then driven downward until final tightening. The strength of the joint comes from extrusion and flow that creates greater interlock depth (see Fig. 4).

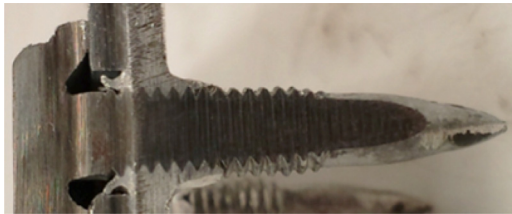


Fig. 4. Flow drill screw steel-Al joint.

This process is not without limitations such as thin gauge materials and the perpendicularity of the screw to avoid skidding. FDS is often used in conjunction with adhesives. Furthermore, there are some concerns for galvanic corrosion so the head of the screw is often covered with a sealer as in the Mercedes SL [18]. Audi was an early FDS user for Al joints and implemented it with pre-drilled holes on the TT and without predrilled holes on the R8 [123]. They also used this for a steel-Al joint on Audi TT production [81]. The method has been shown appropriate for various combinations of steel, aluminium, magnesium and carbon fibre reinforced polymers (CFRP). Szlosarek et al. [236] analysed the damage and fracture mechanisms for joints between fibre-reinforced composites, CFRP, and metals. They found that the peak loads were independent of loading angles albeit they used a predrilled hole in the CFRP. Under pure cross tension load, shear punching caused the characteristic failure mode. Under shear load the CFRP laminate becomes damaged under bearing stress leading to fibre kinking damage. This is just one example of an overall need for additional work to characterize the failure loads and damage mechanisms of various dissimilar material joints under static, dynamic, and fatigue loading conditions.

2.1.3. Clinching

Clinching is a mechanical joining process where the sheet metal parts are joined together by an interlock formed through local plastic deformation without cutting or the use of any external elements such as a fastener or rivet, see Fig. 5. Varis [259] provides a nice description of the tools and process of clinching as well as the modes of failure of the clinched joints. Mucha [169] investigated the locking mechanism in clinching using finite element analysis.

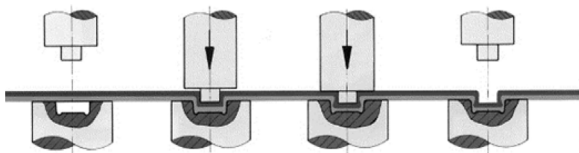


Fig. 5. Process of clinching [259].

To form a clinched joint, the materials to be joined need to have high ductility. Two overlapping sheets are deformed together under the action of a punch and a die in a press machine. The process is relatively simple and it does not produce any heat, splashes, or emissions. "A clinched joint is characterized by a pit on the punch side, and a rise on the die side" [164,259].

Since the joint is formed by the mechanical deformation of the overlapping sheets, clinching can be used to join dissimilar materials, or difficult to weld materials. Varis [260] studies the

suitability of clinching in joining high strength steels in construction. Abe et al. [1] studied the clinch joining of high strength steel and aluminium alloy sheets. It was found that the relatively low ductility of the high strength steel may lead to fracture of the steel sheet. As such, proper die design is necessary to enhance control of the metal flow. Neugebauer et al. [177] introduced a die-less clinching method for joining magnesium sheets. There can be two failure modes for a clinch joint under load: (i) A joint may fail around the neck due to excess thinning and deformation of the sheet metal around the die corner. This happens often if the die corner radius is small. (ii) If the deformation is insufficient and the mechanical interlocking is weak under load, the sheet may separate. The relative strength of this joint is low as compared to the more common self-piercing rivet favoured in the automotive industry for dissimilar material joints. Mori et al. [164] gives an extensive overview of clinching.

2.1.4. Friction stir blind riveting

Friction stir blind riveting (FSBR) is another process for mechanical joining in situations with only single sided accessibility. FSBR was originally proposed by Gao et al. [79]. Unlike conventional blind riveting, no pre-drilled hole is necessary. In this process a blind rivet is rotated at high speeds (6–12,000 rpm), and is then lowered onto the upper surface of the top workpiece. This generates frictional heat thereby softening the workpiece material and enabling the rivet to be driven through the stack-up under reduced force. Once the rivet is driven into place, the blind rivet is upset as in conventional blind riveting, to join the workpieces together (see Fig. 6 and Fig. 7).

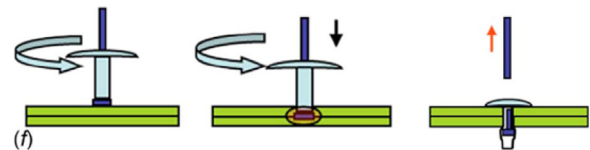


Fig. 6. Friction stir blind riveting Gao et al. [79].

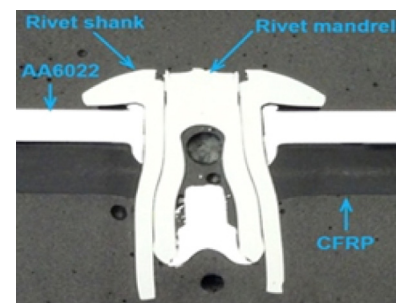


Fig. 7. Friction stir blind rivet in a CFRP-Al joint.

Gao's work was targeted at Al-Al joining and showed that both lap-shear and fatigue strength were significantly better than comparable resistance spot welds. Additional work [154] highlighted the fracture mode (shearing of the workpieces by the rivet followed by a tearing mode) which was the same as conventional rivets, though in FSBR there is a thermo-mechanical zone created by material flow resulting from the rivet insertion which increased the hardness adjacent to the rivet. This effect is enhanced with increased rivet feed rates resulting in slight increases of peak strength.

Lathabai et al. [124] extended the application to include combinations of wrought and cast Al alloys as well as Mg-Al joints. They found that the process is sensitive to stack-up order since the top workpiece impacts insertion force and the bottom workpiece directly affects the failure load since the rivet head on the top workpiece distributes the load over a greater area. Furthermore, they investigated both solid and hollow rivet designs [125] as well as the effect of process parameters. Their major finding was that rivets

with a hollow mandrel head accommodated the workpiece material that was displaced by the rivet. This resulted in lower insertion forces as well as eliminated flash formation at the rivet exit hole.

Min et al. [155] investigated quality issues related to stack-up order in Mg–Al joints. For example placing the relatively brittle AM60 cast Mg alloy on the bottom resulted in semi-brittle fracture on the backside whereas the FSBR exhibited better strength versus conventional blind riveting only when the more ductile Al was the bottom workpiece. Zhang et al. [292] investigated the feasibility of FSBR Mg–Steel joints. They found that with sufficiently high feeding rates even the DP600 material could be pierced at 2200 rpm, though their process development was focused on Mg as the top workpiece. However, in subsequent work [291] they show that having the Mg as the top workpiece resulted in the softer magnesium being extruded downward as the rivet is inserted. This then pushes against the steel bottom workpiece resulting in a considerable gap at the faying interface. With the steel as the top workpiece, it is much stiffer and does not extrude downward resulting in a tighter joint. Lastly, Min et al. [156] investigated CFRP–Al FSBR joints and because of the significant differences in the thermal-mechanical properties both the FSBR process and lap-shear strengths of the CFRP–Al joints were sensitive to stack-up order. The relative brittleness of the CFRP material was found to be limiting the process window robustness.

2.1.5. Self-piercing riveting (SPR)

Self-piercing riveting is extensively described by Mori et al. [164], and is not covered in detail in this paper. In a SPR process, a hollow rivet is pierced through the top sheet and through the influence of a counter acting die, deformed and inserted into the lower sheet (see Fig. 8) [93]. He et al. [92] provide a review of SPR research. Compared to the more traditional methods of sheet material joining, the advantages offered by SPR include the ability of joining dissimilar materials [25,34]. There is no need for pre-drilling as in blind riveting, fast cycle time and ease of incorporating SPR within the predominant Resistance Spot Welding (RSW) based assembly line infrastructure. SPR joints are also believed to have good mechanical strength, in particular, fatigue strength [108]. However, SPR also has several limitations. A given rivet can only manage a limited sheet thickness range, and it requires a die and access in order to deform the rivet; it is difficult for the rivet to flare inside high strength materials. Mori et al. [165] describes a case of plastic joining of ultra high strength steel and aluminium alloy sheets using SPR [165]. The rivet is specially designed for the task using FEM modelling to overcome the potential problems from the differences in material properties.

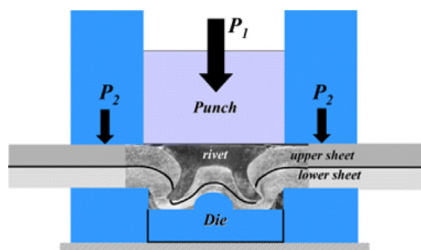


Fig. 8. A self-piercing process [108].

2.1.6. Sewing and filament winding

Joining of dissimilar materials by applying threads or fibres in processes such as stitching, sewing and winding are ancient crafts processes. Sewing is still the main way to join fabrics, leather and other materials for clothing, furniture, bags etc. There are however few industrial cases of automated sewing, typically aided by special purpose customized fixtures. Automation of sewing processes has been investigated by some authors: Seliger and Stephan [215], Kudo et al. [120], Wittig and Rattay [281], Wittig [280] and Kawauchi [113]. The problem is not only the sewing itself, but also the handling of material into and out of the sewing process. Wetterwald et al. [278] shows an example of flexible,

automated sewing of leather and fibre foam with automated handling without pre-programmed robot paths or dedicated fixtures using sensor fusion feedback control.

Filament winding is another process where fibre or thread can be used for joining of dissimilar materials. Fleischer and Schaedel [75] show how filament winding can be used for joining CFRP and steel components for automotive space frame structures, see Fig. 9. Similar processes have been patented, for example to join composite tubes to metallic tubes or fittings: US5288109 A [20], US 4549919 A [19].

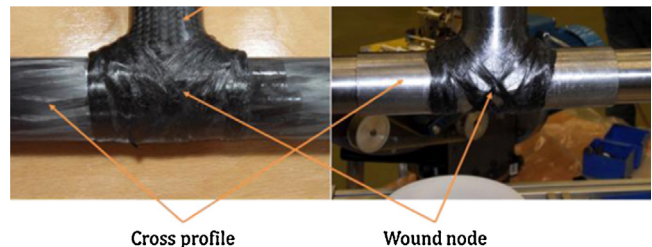


Fig. 9. Filament winding of automotive space frames [75].

2.1.7. Other mechanical joining processes

Mori et al. [164] give an extensive description of joining by forming where the joining workpieces are exposed to a forming process which creates an interlocking grip. Joining by forming can be through hydroforming, roll forming, electromagnetic forming, hemming, seaming and staking. Explosion joining can be a low-cost simple solution for possible challenging tasks such as joining of power lines in the field far from any other energy sources. Mechanical joining by plastic deformation can provide stronger joints than attained by conventional mechanical fastening processes. Another joining process described by Mori et al. [164] is interference fit or friction fit, where joining forces are created through two (or more) parts pressed together. These processes can be used for dissimilar material joining, but problems such as creep or galvanic corrosion must be avoided.

2.2. Chemical joining processes: Adhesion

The word adhesion is derived from the Latin words for to stick (ad = to, hesion = stick) [263] and adhesive bonding has a strong position in modern manufacturing applications [24]. There exist several theoretical mechanisms of adhesion: (i) Adsorption theory, (ii) Chemical bonding, (iii) Diffusion theory, (iv) Electrostatic attraction, (v) Mechanical interlocking and (vi) Weak boundary layer theory. None of the theories are capable of providing a comprehensive explanation for all types of adhesive interaction and joints [23]. Specific surfaces, various mechanisms and/or their combinations may be engaged in the bonding process. Bond formation results in a contact zone (intermediary zone) created between the adherent and adhesive [284]. Adhesive should completely wet the bonding area, but material surfaces will be irregular and voids may occur. The adhesive composition and the contact zone determine the bond characteristics, viscosity of adhesive and surface energy of the substrate [284].

There are several factors defining the adhesive bond performance (lifetime, robustness, etc.) [224], these factors are: (i) Physical and chemical properties of adhesives, (ii) nature of adherents (which materials are to be joined), (iii) type of bonding surface pre-treatment (preparation), (iv) surface wettability and (v) joint design (appropriate adhesive choice). Joint design plays a crucial role in adhesive and curing method choice. Moreover the preparation of the adherent surface is important to joint quality [261]. Wu and Lu [282] describe how a low surface energy leads to the appearance of weak adhesion between polymers and metals. One of the main objectives of joint design is to consider the stress distribution(s): tensile, compression, shear, cleavage, peel and their combinations (see Figs. 10 and 11). Lap joint design with

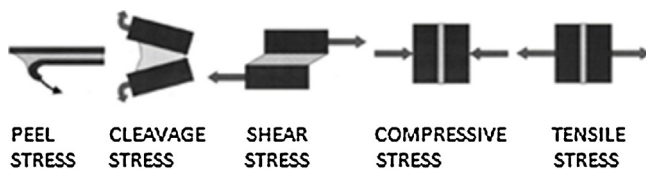


Fig. 10. Stresses in adhesive joints [284].

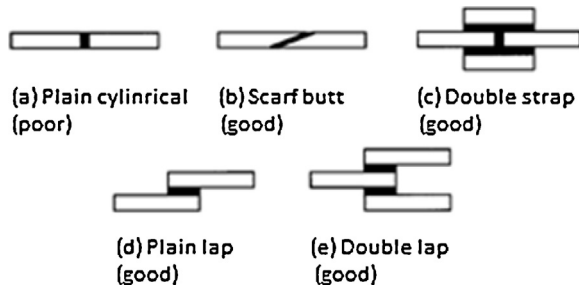


Fig. 11. Selected types of adhesive joint design [284].

predominately shear stress is considered to have more advantages compared to other designs [184].

Adhesive bonding provides possibilities to join materials such as plastics, metals, rubbers, and glass [288]. Adhesives have become widely used in different industry sectors, especially in electronics [286]. For example, adhesive bonding is used in the fibre to glass ferrule attachment in fibre optics manufacturing [284].

Each type of adhesive provides a unique set of performance and processing opportunities [224]. Adhesives are chosen by parameters such as: Performance, Processing conditions, Materials to be joined, Curing type and application type. Curing is the (adhesive) transformation from liquid to solid state (polymerization) which is usually accompanied by physical and chemical changes [2]. Curing is typically induced by heat, electromagnetic curing (light, EM field etc.) and dual curing.

Each adhesive is selected according to its advantages and disadvantages derived from mechanical and chemical properties. Advantages of adhesive bonding are: (i) creation of a continuous bond, (ii) corrosion prevention (sealed joint), (iii) stress distribution over a joint area, (iv) vibration reduction, (v) invisibility of joints within assembly, (vi) minimization of an assembly mass, (vii) no substrate deformation and (viii) minimizations of components in an assembly (Niagu et al. [179]; Small and Courtney [224]; Yacobi et al. [284]).

Limitations to the adhesive joining methods are: (i) adhesive joints are difficult to disassemble, (ii) surface preparation requirements (strength of the bond requires special condition of adherent's surface), (iii) extra time needed for polymerization, (iv) limited thermal resistance, and (v) bond attenuation from atmospheric agents, degradation and chemical agents. Typical causes of joint failures are poor design, unprepared surface, improper adhesive selection for the substrate or difficult operating environment conditions [224].

2.3. Thermal fusion joining processes

2.3.1. Electric arc welding

The most common process for fusion joining is electric arc welding, for example Gas Tungsten Arc Welding (GTAW), Shielded metal arc welding (SMAW) and Gas metal arc welding (GMAW). These methods can be used for "easier" dissimilar metals joining, such as carbon steel to stainless steel. The challenge is the relative larger size of the Heat Affected Zone (HAZ) and the molten pool compared to the other methods described in this paper, which could lead to a large zone of brittle Intermetallic Compounds (IMC) when welding dissimilar metals. The selection of filler material is critical for the quality of the dissimilar welds. Mittal and Sidhu

[162], Chen et al. [53], and Liu et al. [136] studied the microstructure of Ti-Al GTAW and the formation of IMC. Bahrami et al. [21] studied the mixing of two dissimilar metals in the GTAW pool, both numerically and by experiments. Show how the application of Activating Fluxes can enhance the GTAW penetration.

2.3.2. Plasma sintering

Sintering goes back to the remote past and the process for forming bricks [170]. As a science it appeared in the 1920–1930s [245]. Metallic powders were sintered (sinter joining) in 1933 [241]. In the 1950s Lockheed Missile Company developed 'spark sintering' with the use of electrical discharge [170]. This has evolved into 'Spark Plasma Sintering' process (SPS) [230,299]. The physics of the process are not yet fully understood however, and the existence of plasma in the sintering process has been questioned [103]. SPS has thus by some been renamed pulsed electric current sintering (PECS) [29].

SPS is considered to be an effective method for consolidating different types of materials [65,104]. The method provides rapid sintering by self-heating [225]. Intermetallic compounds (IMC), metal and ceramic matrix composites, nanostructured materials, amorphous materials, highly refractory metals and ceramics can all be processed using SPS (see Table 1). This process provides several advantages including sintering of materials like tungsten carbide [183], high sintering speed, low power consumption, reasonable performance, safety and reliability [65,139,158].

Table 1
Materials obtained using SPS [57].

Groups	Materials
Metals	Fe, Cu, Al, Au, Ag, Ni, Cr, Mo, Sn, Ti, W, Be, Ir
Alloys	W-Ni-Fe, W-Cu, Cu-25Cr, Ni-49Ti, Fe-5Mn, Ti-6Al-4V, Ti-Al-B, Al-Si-Cu-Fe
Ceramics	Oxides: Al ₂ O ₃ , Y ₂ O ₃ , ZrO ₂ , SiO ₂ , TiO ₂ , HfO ₂ , MgO, ZnO, SnO ₂ Carbides: SiC, B ₄ C, TaC, TiC, WC, ZrC, VC Nitrides: Si ₃ N ₄ , TaN, TiN, AlN, ZrN, VN, CN _x Borides: TiB ₂ , HfB ₂ , LaB ₆ , ZrB ₂ , VB ₂ , MgB ₂
Cermets and composites	Si ₃ N ₄ + SiC, BN + Fe, Ti + TiB + TiB ₂ , YSZ, (Na _{1-x} K _x)NbO ₃ + PbTiO ₃ , Al ₂ O ₃ + Ni, Al ₂ O ₃ + TiC, Al ₂ O ₃ + SUS, Al ₂ O ₃ + Nd ₂ Ti ₂ O ₇ , Al ₂ O ₃ + SiC, Al ₂ O ₃ + GdAlO ₃ , Al ₂ O ₃ + Ti ₃ SiC ₂ , Al ₂ O ₃ + C, ZrO ₂ + Ni, ZrO ₂ + SUS, ZrO ₂ + Y ₂ O ₃ , ZrO ₂ + Al ₂ O ₃ + TiC _{0.5} N _{0.5} , WC/Co ± VC, WC/Co + Fe
Intermetallics	TiAl, NiAl, NbCo, NbAl, Sm ₂ Co ₁₇ , Nd-Fe-B, (Bi,Sb) ₂ Te ₃ , Al-Al ₃ TiSiC + AlN
Other	Organic materials (polyimide, etc.)

SPS is a viable method for joining dissimilar materials in a high temperature range and for joining ceramic matrix composites [48,86,143]. Successful joining of silicon carbide and graphite at 2000 °C with a resulting tensile strength of 18 MPa has been reported [182]. No cracks or delamination were identified in the samples. Liu et al. shows how SPS can be utilized for joining dissimilar (nanocrystalline) sintered materials such as Ni₃Al and TiC/Ni₃Al [139]. SPS has shown to be an effective approach for joining of CVD-SiC coated C/SiC composites, directly and with glass-ceramic (CA), a SiC + 5 wt% B₄C mixture and pure Ti foils as joining materials [198]. Furthermore have SPS been used for Ti to Steel joining, without the brittle Fe-Ti intermetallic compounds (IMC) and shape distortion of parent materials [157]. A joint of Ti-6Al-4V to low alloy steel made at 950 °C was reported to have a maximum tensile strength of 250 MPa [158].

2.3.3. High energy beam welding

Laser beam and electron beam welding are high-energy beam welding methods, where the energy density is typically 10¹⁰ to 10¹³ W/m². There are generally two different welding modes: (i) melt-in/conduction mode or (ii) keyhole mode. The conduction

mode works by heat conduction and is best suited for thin sheets [149]. Keyhole, on the other hand, has higher energy density, vaporizes a cavity, and melts the surrounding material. The keyhole is thus suited for thicker materials, and could require filler material. High energy beam welding is a promising method for welding of dissimilar materials and there are many examples of both metals and polymers in the literature.

Sun and Ion [233] reviewed the laser welding of dissimilar materials. They pointed at advantages of laser compared to conventional welding; the ability to fuse dissimilar metals and alloys and overcome the problems with large differences in thermal conductivity. The small size and accuracy of the beam provides control of the microstructure, and a small heat-affected zone (HAZ) results in rapid solidification and less grain growth. Formation of a brittle layer of IMC can occur, although the problem is smaller in high-energy beam welding than conventional arc welding. Fig. 12 shows a table from Sun and Ions work [233] estimating the laser weldability between different metals.

Laser weldability of binary metal combinations. (E - excellent, G - good, F - fair, P - poor, * - no data)																			
	W	Ta	Mo	Cr	Co	Ti	Be	Fe	Pt	Ni	Pd	Cu	Au	Ag	Mg	Al	Zn	Cd	Pb
Ta	E																		
Mo	E	E																	
Cr	E	P	E																
Co	F	P	F	G															
Ti	F	E	E	G	F														
Be	P	P	P	P	F	P													
Fe	F	F	G	E	E	F	F												
Pt	G	F	G	G	E	F	P	G											
Ni	F	G	F	G	E	F	F	G	E										
Pd	F	G	G	G	E	F	F	G	E	E									
Cu	P	P	P	P	F	F	F	F	E	E	E								
Au	*	*	*	P	F	P	F	F	F	E	E	E							
Ag	P	P	P	P	P	F	P	F	P	F	E	F	E						
Mg	P	*	P	P	P	P	P	P	P	P	P	F	F	F					
Al	P	P	P	P	F	F	P	F	P	F	P	F	F	F	F				
Zn	P	*	P	P	F	P	P	F	P	F	F	G	F	G	P	F			
Cd	*	*	*	P	P	P	*	P	F	F	F	P	F	G	E	P	P		
Pb	P	*	P	P	P	P	*	P	P	P	P	P	P	P	P	P	P	P	
Sn	P	P	P	P	P	P	P	F	P	F	P	F	F	P	P	P	P	P	F

Fig. 12. Laser weldability of dissimilar metals [233].

Use of filler foils with rare earth minerals has produced promising results in reducing brittle IMC. Enz et al. [69] described laser welding of dissimilar aluminium alloys (7XXX and 5XXX alloys) using a patented process with a vanadium filler foil in addition to conventional filler wire (see Fig. 13). This approach led to formability improvements of the joints.

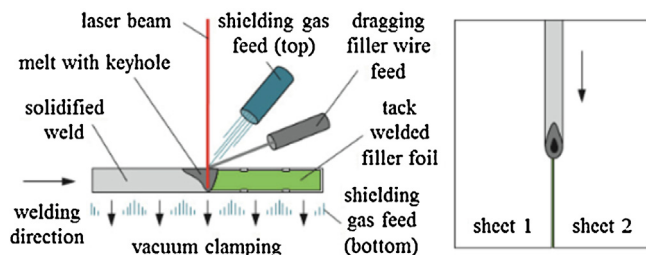


Fig. 13. Laser beam welding with filler wire and filler foil [69].

Tomashchuk et al. [246] show an example of Keyhole laser beam welding of aluminium alloy AA5754 to titanium alloy Ti6Al4V. They investigated the effects in IMC from rapid thermal cycles, different morphologies of contact interfaces, and laser beam positions. They could demonstrate a maximum linear tensile force of 220 MPa for a 2 mm thick weld. Li et al. [133], show how some metals such as brass and stainless steel have a very good weldability due to unlimited solid solubility. IMC is thus absent in these joints. Yao et al. [285] showed how Cu and steel could be butt welded by fixing the laser beam on the steel side. "A turbulent

bursting behaviour in the welding pool led to the penetration of liquid metal into Cu". Similar results were shown by Al-Jamal et al. [4] when welding copper and H13 tool steel using a Nd:YAG laser.

A typical approach in lap joints on thermoplastic polymers is Through Transmission Laser Welding (TTLW) where the upper part is transparent, transmitting the laser beam and the lower part is absorbing the laser energy. Juhl et al. [110] describe a method to predict the weldability of dissimilar polymers using a model of the correlations of the laser weld strength and polymer properties. They show by experiments that their model predicted the weldability of 6 dissimilar polymers from their chemical and physical properties. Wang et al. [270] has investigated the welding of PET and Polypropylene (PP), and the effect of the molten pool on the shear strength of the joint. They have developed a finite element model capable of predicting the molten pool geometry. The welding method can also be used to create polymer-metal bonds. Wang, et al. [271] show an example of laser transmission lap joining between PET and titanium with promising results. Even metal-metal joints can utilize this effect: Mecco et al. [146] describe lap joint laser beam welding of 2 mm thick steel XF350 steel to 6 mm thick aluminium (AA5083-H22). The bond is created by: "heat conducted through the steel plate to the steel-aluminium interface, where the aluminium melts and wets the steel surface" and a tensile shear load of the bond of 21.4 to 31.3 kN is achieved. The experiments exhibited, however, a 4–20 μm thick brittle layer of IMC. Similar results are shown by Chen et al. [54].

Laser welding is also applicable for welding inhomogeneous materials. Salonitis et al. [210] describes experiments and numerical analysis with CO₂ laser welding sandwich plates consisting of two IF 260 steel plates divided by a 45 μm viscoelastic polymer. Although some of the core vaporizes, the experiments show promising results regarding mechanical characteristics. Bassani et al. [28] investigated the weldability of Al/SiC Metal Matrix Composites (MMCs) using a laser.

2.3.4. Brazing and soldering

Brazing and soldering are joining methods where a filler material is heated to its melting temperature and applied between the mating parts of the joint without melting the base materials. The filler has a lower melting temperature than the parts to be joined. It is a well-known technology used to join dissimilar materials, especially ceramics to metals [42,200,213,244]. Brazing is also widely used to join dissimilar metals which can't be joined by welding processes because of complicated geometry or incompatibility of metals [42]. Braze fillers have a melting temperature above 450 °C, and soldering fillers below. Connection of materials obtained in brazing processes are typically stronger than in soldering, and is close to a natural connection [244].

Brazing processes include laser brazing [200,213], furnace brazing [213], arc brazing and vacuum brazing [27]. Laser brazing gives short heating time and small heating area [213]. Vacuum brazing is an economical method which helps to prevent oxidation of surfaces and the introduction of impurities [42]. Furnace brazing is used to join dissimilar materials such as aluminium to stainless steel, and high quality joints can be achieved at 600 °C by using an eutectic filler (Al-Si alloy) [202]. In electronic, aerospace and automotive sectors there is a need to join magnesium alloys with metals such as titanium and aluminium [226,274]. A brazing process at temperatures of 500 °C using Sn-30Zn solders is beneficial for joining Mg and Al [274].

Transient liquid phase soldering (TLPS) is a lead free soldering and a result of combination of conventional soldering and diffusion [58]. One of the advantages compared to other soldering processes is less IMC [39]. This joining method has found increased use for manufacturing of power electronic modules used in wind turbines, solar power panels and electric cars [89,105,114]. The lifetime of power modules has increased after introduction of TLPS [115]. Joining of two materials with different melting temperature such as titanium to aluminium alloys can be done by laser brazing without adding filler materials [226].

Metallic interlayer bonding can be an alternative when joining ceramics and metals, with fewer problems from thermal expansion mismatch and suitability at higher temperatures. Jadoon et al. [109] demonstrated how a thin interlayer foil of Cu can create a bond between High-temperature steel (Fecralloy) and Si₃N₄ ceramics when bonded in a 1200 °C furnace under vacuum. They achieved a shear strength of 67.5 MPa at 1100 °C. They found an indication of reactive wetting where Fe, Cr, Al and Cu infiltrated the silicon nitride, and Si and N diffused into the steel.

2.3.5. Resistance spot welding

Resistance spot welding, RSW, has been the mainstream solution for steel-dominated automotive body-in-white (BIW) production. It can easily be automated, is very flexible, and since the weld gun electrodes are clamped, small gaps between the sheets can be levelled. A number of researchers have applied RSW to dissimilar Al-steel joints [91,163,181,191,232,257,267,297], as well as material combinations including Mg-steel [138], glass-steel [78], Cu-Ni plated steel [178], stainless steel-Ti [253], Ti-Al [193], and Al-Mg [90,106]. The benefits of enabling the RSW of Al-steel would be the re-use of existing infrastructure to join both like and dissimilar material combinations and the significant cost avoidance necessary to retool for a new joining process. There are, however, a number of fundamental issues that need to be addressed to achieve a high quality weld.

The first issue is the aluminium oxide surface layer and how this impacts contact resistance. Current solutions include breaking the oxide layer and reducing the contact resistance between the electrode and aluminium workpiece surface by rotating the electrode during welding [197] and a novel multi-ring domed electrode [219]. Wang et al. [268] describes the concept of an initial asperity-softening phase. Points of localized breakdown along the faying interface concentrate current and result in increased temperature leading to localized melting of the aluminium. Miyamoto et al. [163] addressed the issue of the oxide along the faying interface with zinc-coated steels. Their approach was to heat the stack-up so that the zinc coating melts and reacts with the aluminium to form an Al-Zn eutectic phase. This acts to mix the aluminium oxide layer into the eutectic melt. At this point the electrode force is increased to squeeze out the molten eutectic and oxide, thereby bringing fresh aluminium into contact with the steel. The current is applied only long enough to form a bond. The welding time can then control the resulting intermetallic layer thickness. Ueda, et al. [256] furthered this work with higher strengths at lower currents using Al-Mg-Zn coated steels. This coating melts at a lower temperature than Zn and Al-Zn coatings but is still able to remove the coating and oxide layer sufficiently through expulsion of the eutectic reaction products.

The second issue is the difference in bulk resistance between the steel and aluminium. This will centre the Joule heating towards the steel (Fig. 14). Since aluminium melts at significantly lower temperatures, the aluminium will start to melt along the faying interface forming a weld nugget within the aluminium prior to any nugget formation within the steel. Thus, since both the copper electrode and high thermal conductivity of the aluminium act as a heat sink, the aluminium weld nugget directionally solidifies from

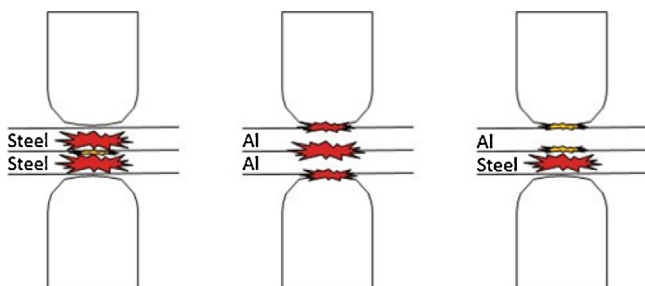


Fig. 14. Joule heating during resistance spot welding of various material combinations. Note the severe imbalance for Al/Steel stack-up.

the electrode/Al sheet interface towards the faying interface depositing any gas/shrinkage porosity.

And finally there is the issue of IMC formation along the faying interface as the iron diffuses into the molten aluminium. The challenge is to drive crack propagation through the aluminium heat affected zone to create a weld button versus interfacial fracture through the brittle IMC and porosity along the faying interface. Thus, researchers need to understand the effect of IMC thickness and morphology on strength. Qui et al. applied Electron Microprobe Analysis (EMPA) imaging of A5052 Al-cold rolled steel fracture surfaces to show that fracture occurred in the base Al material when the IMC layer was thinner than 1.5 μm and having a discontinuous morphology, but fractured in the reaction layer for greater thicknesses which had a continuous morphology [188]. However, within the range of discontinuous IMC, the tensile strength increased with increased discontinuous reaction layer fraction [190]. Another challenge is to understand the relative impact of the IMC layer on different mechanical tests. For example cross-tension test results of Al-steel which exhibited significantly lower joint efficiencies, approximately 30%, as compared to approximately 90% for lap-shear test results at a given nugget size [192].

A number of researchers have investigated the formation of the intermetallic layer [191] and its effect upon weld strengths because of its deleterious effect. Zhang et al. [298] used scanning electron microscopy of a partially failed tensile specimen to clearly show crack initiation at the interfacial IMC layer (chiefly Fe₂Al₅ phase) and propagation through the IMC layer and partially through the Al alloy fusion zone adjacent to the IMC layer. The cross-tension results [163] from 6000-series Al welded to low-C steel indicate peak strengths below an IMC layer thickness of 2 μm with a significant drop in properties at 4 μm with little variation in the range 4–12 μm, refer to Fig. 15.

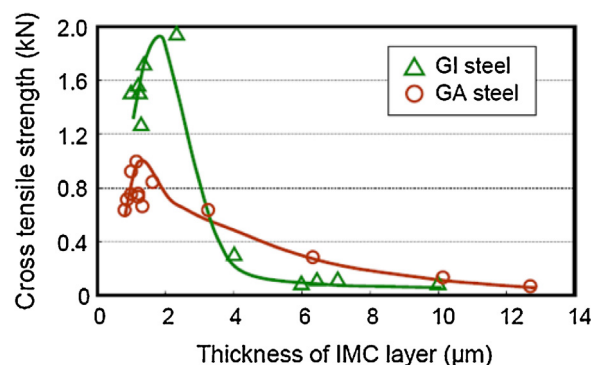


Fig. 15. Relation of Cross tensile strength of RSW welded Al-Steel to Fe_xAl_y intermetallic layer thickness [163].

Qiu et al. [191] show a variation of IMC layer thickness peaking at approximately 6 μm in the centre of the weld nugget region with Fe₂Al₅ adjacent to the cold-rolled steel and FeAl₃ adjacent to the A5052 Al alloy [188]. Wang et al. [267] noted the same intermetallic formation for both A1050 and A2017 welded to cold-rolled steel, though the Fe₂Al₅ adjacent to the cold-rolled steel, was thinner for the A2017 alloy. They attribute this to the Cu alloying element diffusion reducing the Al atom activity coefficient thereby inhibiting the anisotropic growth of Fe₂Al₅. Qiu et al. [189] noted similar retarded growth rates of Fe₂Al₅ IMC layers in Al-austenitic stainless steel versus Al-cold rolled steel joints and attributed that to Cr atoms reducing the Al atom activity coefficient. On the other hand some alloying elements such as magnesium are very reactive and promote IMC growth, thereby reducing joint strength for example, from 1200 N with A1050 aluminium down to approximately 400 N with A5056 (4.5 at% Mg) welded to mild steel [106].

One way to affect the Fe-Al intermetallic formation is to introduce an interlayer. Hwang et al. showed that introduction of pure Al between A5056 and mild steel diluted the Mg content and

reduced the IMC layer thickness [106]. Zhang et al. [296] introduced an AlSi12 interlayer between Al and steel creating an IMC layer composed of $\text{Fe}_2(\text{Al,Si})_5$ and $\text{Fe}_4(\text{Al,Si})_{13}$. Similar to other alloying elements, they found that the Si atoms restricted growth of the $\text{Fe}_2(\text{Al,Si})_5$ intermetallic layer. This is in accordance with research showing that the Si atoms block the easy diffusion paths and thereby affect the growth kinetics of the Fe–Al IMC [287]. Choi et al. [55] introduced an Al–12Si braze at the faying interface during RSW and created a more uniform interface to the steel, though noted fracture along the IMC–Al base material interface resulting in relatively low strengths. Tu et al. [253] welded pure Ti to 304 stainless steel using an A5052 sheet inserted between creating a weld nugget in the Al alloy, a diffusion bond with an IMC of 160 nm between the Ti and Al alloy and an IMC consisting of FeAl_3 and Fe_2Al_5 between the Al and stainless steel, respectively. Fracture occurred either along this IMC layer, within the Al alloy adjacent to the IMC or along the Ti–Al IMC layer with increasing weld currents.

One of the first proposed concepts to avoid excessive IMC formation during RSW of Al to Steel was the use of a transition material such as an Al–Steel clad material [91] to create like-material interfaces during fusion welding and leverage the relatively good Al–steel interface created during cladding. Oikawa et al. [181] showed slightly thicker IMC (Fe_2Al_5) layer thickness with an Al–steel clad transition material versus direct Al–steel welding, approximately 5 versus 2 μm , respectively, but a better mechanical performance with the clad material. They attributed this to differences in fracture mode in part due to geometrical differences related to the insertion of the clad material. Significant process window development was done by Sun et al. [232] and in related work FEM of the nugget formation [231]. Unfortunately, this process introduces both an additional production step as well as a layer of material creating a gap along the seam in between welds.

Wang et al. [269] discussed the strategy of using an interlayer when welding two materials with comparable melting point such as Al and Mg or a cover plate when there is a melting point disparity as with Al–Steel. The cover plate concept addresses the Joule heating imbalance in dissimilar materials. The aluminium is sandwiched between two pieces of steel creating a balanced heat generation as shown by [192] in an attempt to create a weld nugget towards the centre of the aluminium which then grows out and eventually reaches the faying interface. The idea here is to limit the amount of time molten aluminium interacts with the steel thereby minimizing the intermetallic layer thickness. Qiu et al. [189] experimentally achieved a larger nugget and high tensile shear loads under relatively low welding current conditions for Al–Steel using a 1 mm thick cold rolled steel cover plate on the Al side. This is a result of an overall greater heat generation for a given weld schedule with a cover plate [192]. Low welding currents are desirable since higher current levels can cause excessive electrode indentation on the Al side which in turn reduces peak load and energy absorption [166]. Qiu et al. [193] also successfully applied this technique to Ti–Al joints that also have a significant melting point disparity. Pasic et al. [185] applied the commercial DeltaSpot RSW process originally developed for Al RSW using a CrNi process tape on the Al side and a Ni-coated band on the steel side and measured a 2.5 μm IMC layer thickness. Da Silva et al. [62] also used DeltaSpot but were not able to change the heat imbalance and move the porosity away from the Al–Steel faying interface, which deteriorated the mechanical properties. Another method to impact the heat imbalance between the Al and steel is through manipulation of electrode materials or geometries. There is limited information published, though most welding Al directly to steel use a matching pair of F-type rounded electrodes with dome radius 40 mm and a face diameter of 6 mm [55,181,256,257]. Truncated, 45° cone with a 8 mm face diameter has also been noted [166]. However, Zhang et al. [296] used a flat tip electrode with 10 mm face diameter on the steel side and a 35 mm dome radius electrode on the Al side to concentrate the current and counteract

the high thermal diffusivity on the Al side. They report an increase of approximately 65% in weld nugget diameter and 70% in lap-shear strength attributed to a thinner IMC layer compared to when conventional F-type electrodes are employed.

2.4. Thermal joining, solid state processes

2.4.1. Friction stir welding

Friction Stir Welding (FSW) was invented in 1991 by The Welding Institute (TWI) in UK and it was originally intended for similar material joining of Al alloys and other light-weight materials [116,159]. The usage of lightweight materials is still considered to be a driving force for the FSW joining technique evolution [239,258], and FSW is a candidate for joining of dissimilar materials in hybrid structures [59]. FSW, Friction Stir Processing, Friction Stir Casting (also known as FTMP), Friction Stir Micro forming, Friction Stir Powder Processing, Friction Stir Channelling and Friction Stir Spot Welding (FSSW) are all different branches of the Friction Stir process family [116]. FSW minimizes brittle intermetallic phases, metallurgical incompatibility, differences in melting points and thermal mismatch [277]. Mori et al. [164] describe FSW in more detail.

FSW is used in several industry sectors [174] and is a solid-state process where a rotating stirring tool softens the material by frictional heat and the welded materials are mechanically stirred and bonded. The materials are usually not melted during the joining process and their characteristics remain largely unchanged (see Fig. 16).

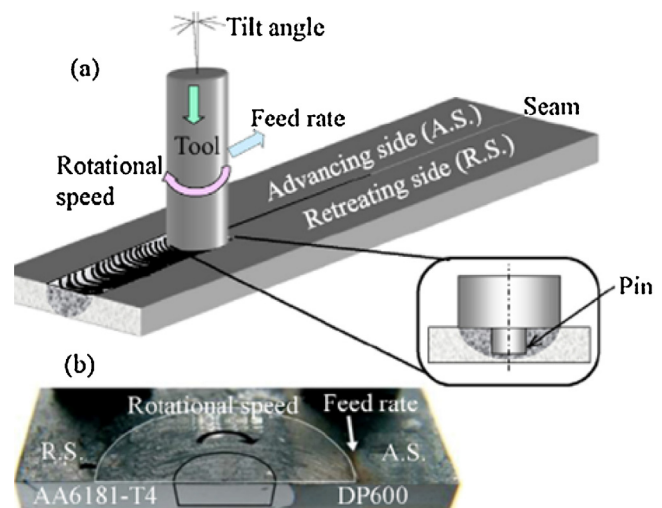


Fig. 16. (a) FSW process for joining workpieces and (b) welded aluminium and steel (AA6181–T4 and DP600) [59,164].

Advantages of this process are: environmentally friendly, non-consumable tool, little or no post-processing such as grinding, removal of residual stresses, corrosion resistance, no filler material, doesn't require oxide removal, cost effectiveness and the possibility to create dissimilar material joints [144,173]. Disadvantages can be: productivity and a pinhole at the end of the welds [240]. According to Sahin [207] the main parameters influencing weld quality are: type of material(s), angle of tool (usually 90°), traversing tool speed, rotation speed, pressure of the tool, pin length and diameter, pin geometry and shoulder diameter. The shoulder produces additional heat, and the greater diameter the larger the weld. See [194] for a review of friction stir welding tools. The process allows for the production of butt-, corner-, lap-, T-, spot-, fillet- and hem joints and also hollow joints (tanks, tubes, pipes) [206,207]. The processing tool creates simultaneous rotation and translational motion which leads to asymmetry between the adjoining sides [218].

The weld microstructure is divided into four regions [116,258] (see Fig. 17): (i) Unaffected material (a and g)—material of the

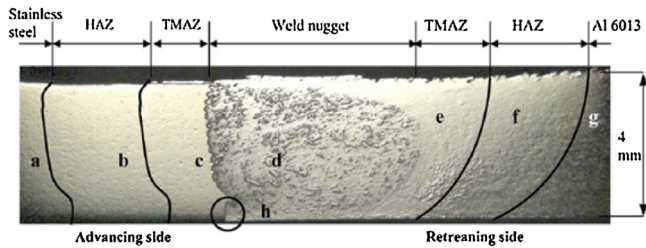


Fig. 17. Cross section of friction stir welded Al6013-T4 alloy to X5CrNi18-10 stainless steel [258].

metal which is not affected by deformation. (ii) HAZ—heat affected zone (b and f)—thermal cycle affected microstructure and mechanical properties, no plastic deformation, (iii) TMAZ—thermo-mechanically affected zone (c and e)—area of material's plastic deformation, both microstructure and mechanical properties are affected, recrystallization takes place here, and (iv) weld nugget—recrystallized area of the TMAZ, possesses different grain structure, 'onion ring' (defines material mixing for the process) effect is seen in this region. The FSW microstructure is, however, still not yet fully investigated [76,159].

Mubiayi and Akinlabi [168] give a general overview of the friction stir welding of dissimilar materials, including aluminium, steel, magnesium and titanium. Other examples include FSW of aluminium alloys with copper [167] and magnesium alloys [137]. The major concern is the formation and effect of IMC as exemplified by a recent investigation of the formation of IMC compounds in FSW Al-Steel and their effect upon mechanical properties [228]. Duffie and Pfefferkorn [60] have studied FSW of two different aluminium alloys with a difference in solidus temperature of nearly 100 °C. They suggest tool offset and utilization of the FSW "cold" less retreating side to avoid weakening of the joint. Mishra and Ma [159] and Khaled [116] have studied the use of FSW for dissimilar metals joining (see Table 2 and Table 3).

Many authors could report successful joining of steel and aluminium. Uzun et al. [258] joined Al 6013-T4 to X5CrNi18-10 steel). Watanabe et al. [277] managed to obtain Al alloy to steel

Table 2
A summary of FSW dissimilar joining [159].

Materials	Plate thickness (mm)	Rotation rate (rpm)	Traverse speed (mm/min)
2024Al to 6061Al	6.0	400–1200	60
6061Al to 2024Al	12.7	637	133
2024Al to 1100Al	0.65	650	60
5052Al to 2017Al	~5.3, 3	1000, 1250	60
7075Al to 2017Al	~5.3, 3	1000, 1250	60
7 × 1 × Al (Sc) to 7 × 5 × Al (Sc)	~5.3	1000	60
7075Al to 2017Al	3	1250	60
7075Al to 1100Al	3	1250	60
5083Al to 6082Al	5.0	-	170–500
2024Al to D357	-	-	-
6061Al to A356	4.0	1600	87–267
2024Al to 7075Al	25.4	150–200	76.2–127
20 vol.% Al ₂ O ₃ /6061Al to 10 vol.% SiC/A339	6.5	800	60
20 vol.% Al ₂ O ₃ /2014Al to 2024Al	4	1120	120
6061Al to copper	6.0	400–1200	60–180
2024Al to copper	6.5	650	60
2024Al to silver	6.0	650	60
Copper to brass	6.2	1000	60
1050Al to AZ31	6	2450	75
6061Al to AZ31B	-	800	75
6061Al to AZ91D	-	800	75
AZ91D to AM60B	-	2000	75
5083Al to mild steel	2	100–1250	25
6061Al to AISI 1018	6	914	140

Table 3
Joining difficulty and process options for dissimilar materials combinations. 1 = not difficult, 3 = moderate, 5 = extremely difficult. A = adhesive, B = brazing, F = fusion welding, M = mechanical, N = non-fusion welding, S = soldering.

Dissimilar materials		Joining difficulty	Joining options in preferred order
Material 1	Material 2		
Metal	Metal	1–5	A,B,S,M,F,N
	Ceramic	3–5	B,A,N,M
	IMC	3–5	B,N,M,F
	Thermoplastic polymer	1–3	A,M
	Thermoset FR polymer	1–3	A,M
Ceramic	Ceramic	2–4	A,M,B,N,F
	IMC	3–5	B,M,F
	Polymer	2	A
Thermoplastic polymer	Thermoplastic polymer	1–2	A,F/N, M
	Thermoset FR polymer	1–4	A,F/N, M

joint with a maximum tensile strength of 86% with a small amount of intermetallic compounds at upper weld zone. Coelho et al. [59] describes joining between two grades of high strength steel HSS (DP600 and HC260LA) and AA6181–T4 Al alloy, having 80% tensile strength of Al alloy, no plastic deformation of HSS, complete and crack free bonding of both materials.

An industrial case of FSW of aluminium to steel is the Honda Motor Co., Ltd case of front sub-frame used in the Honda Accord from 2013 [96]. The new technology results in 25% weight reduction, 50% less welding electricity consumption, 20% increased rigidity of the mounting point and welding strength similar to arc fusion welding (see Fig. 18).

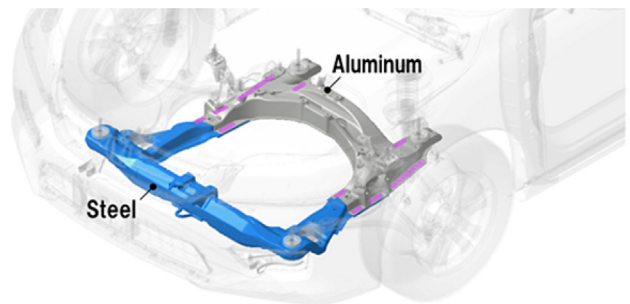


Fig. 18. Honda Accord front sub-frame using Al-Steel FSW [96].

Steel–steel FSW has also been reported. Sahin [206] demonstrates joining of HSS–S 6-5-2 and low carbon steel AISI 1040. Sahin [206] concludes that tensile strength of the joint depends on the friction time and pressure, and the tensile strength of the joint is almost equal to tensile strength of AISI 1040, although a decarburization zone appears in the medium carbon steel next to the weld (the weakest place in the joint). FSW for welding thermoplastics is demonstrated by some authors. Troughton [252] has emphasized important factors to be taken into account for plastic welding such as welding speed and friction energy. Nelson et al. [175] invented and patented a special friction welding tool, which solved problems with insufficient frictional energy. Sorensen et al. [227] describes how FSW can be used for joining different thermoplastics (polypropylene, high density polyethylene and ultra high molecular weight). Ratanathavorn [195] has reported about joining of Al to thermoplastics using ESAB SuperStir. The author managed to join AA6111 and AA5754 to polypropylene (PP), polyamide-12 (PA-12), PET fibre-reinforced polyethylene terephthalate (PET-PET) and glass-fibre-reinforced polyamide (PA-glass). All joints were formed by creation of a stir zone of aluminium chips, filled in by melted polymer.

2.4.2. Friction bit joining

Friction bit joining (FBJ) uses a consumable bit and was originally developed for Al-steel or other light metal-steel joining.

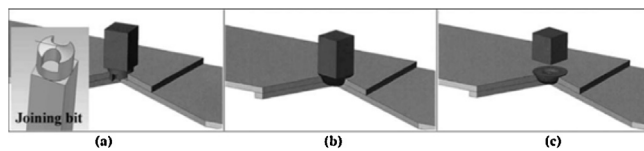


Fig. 19. FBj: (a) cutting, (b) joining, (c) rapid stop [102].

The principle is for the rotating bit to cut through the Al top sheet and then engage the steel bottom sheet. Frictional heat creates a diffusion bond between the joining bit and steel bottom workpiece whereupon the spindle is stopped suddenly similar to inertia drive welding [153]. The rotation of the steel bit results in alternating bands of bit material and steel bottom workpiece material [102] similar to what is observed in friction stir welds of dissimilar alloys. Fig. 19 shows a schematic illustration of the FBj process.

The advantage of this process over self-piercing rivets (SPR) for example, is that it can be used with steel strengths >1 GPa which is considered the typical limit for Al-steel SPR joints. The dominant fracture mode is fracture of the Al top workpiece around the joining bit. The FBj joint strength for 1.8 mm Al 5754-O to 1.6 mm DP590 averaged 6.4 kN, which was greater than the 5.0 kN achieved for SPR joints. No explanation for this is provided though, [152] since the fracture mode for both are fracture of the Al top sheet. The final joint strength is found to be a function of both bit design and process parameters [152].

A recent advancement to FBj is friction element welding developed for joining Al to ultra-high strength steel. The friction element plasticizes the Al and the tip design causes the plasticized material to be transported upwards forming flash which is collected by a groove on the underside of the head [147]. One disadvantage is that the head protrudes from the upper surface (as does FSBR from the underside) whereas FBj is flush similar to SPR. Meschut et al. [147] discuss a variant referred to as Resistance Element Welding (REW) where there is a pre-punched hole in the top sheet which they show can be aluminium or CFRP. However, Hou et al. [97] propose the method of piercing the top sheet with the welding rivet by applying the insertion force with the welding electrode, all the while applying current to soften the light metal top sheet thereby eventually welding the rivet to the steel bottom sheet. All of the aforementioned methods can be applied with adhesive along the faying interface, refer to [148].

2.4.3. Friction welding

Friction welding is a solid state joining process where the two workpieces are heated to a plastic-state with the use of an upsetting force, which displaces the materials and creates the weld. When the heat is generated by the relative motion of two metallic workpieces in contact under a compressive load, the processes can be categorized as (i) rotary friction or spin welding, or (ii) linear friction welding where the chuck holding the specimen oscillates laterally rather than rotating.

Materials welded by friction welding are typically metals and thermoplastic polymers. Disadvantages are geometry constraints and that the rate of heat generation is not uniform over the interface. This causes the HAZ to have non-uniform thicknesses and also the possibility for IMC when welding dissimilar metals. These shortcomings are addressed by orbital welding [254] though very limited research work has been published on this. An inherent advantage of friction welding is significantly lower operating temperatures. Since no melting occurs there are no melting or solidification-related defects such as oxide films, gas porosity, or solidification hot cracking. Furthermore, the weld strength in like-material welds is often stronger than the base material, and since the overall heat input is significantly lower than fusion welding processes, the heat affected zone is smaller and there is typically less distortion and less intermetallic formation in dissimilar metal joints.

Friction welding can be divided into two stages. First stage is the friction or rubbing stage forming a plasticized layer [208]. The second stage (forging or upsetting stage) is applied with a fully plasticized layer and the desired level of heating along the faying interface, and an increase of axial load i.e. forging pressure results in axial shortening, thereby extruding material out of the original area of contact (see Fig. 20).

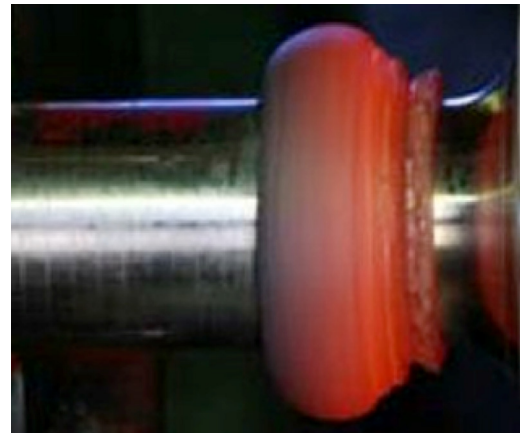


Fig. 20. Material being extruded out of the area of contact during dissimilar metal friction joining.

Uday et al. [254] completed a well-documented review of the types and mechanisms of friction welding and resulting micro-structure and properties of both similar and dissimilar material joints. Three important process parameters have been shown to impact bonding: speed, pressure, and time [121,132,254]. Heating time is typically minimized to reduce waste and overall IMC layer thickness [107]. Fratini et al. [77] have studied linear friction welding of AA6082-T6 aluminium, and described empirical determined process windows.

Ashfaq and Rao [16] make note that the starting location of bonding is a function of speed and pressure; at low friction pressures and high spindle speeds bonding initiates at the centre. When the friction pressure increases the trend reverses. Bhamji et al. [32] showed increasing weld strength with increased pressure during linear friction welding of Mg to Al and attributed this to a reduction of Mg-Al IMC weight fraction, though they were not able to eliminate the IMC completely, and thus never achieved a joint efficiency of 100%. Akbarimousavi and GohariKia [3] preheated 316 stainless steel prior to welding to Co-Ti in order to achieve more uniform deformation across the interface. However, the preheating oxidized the steel. This will be retained at the faying interface unless sufficient forging pressure was applied to clean off the surface, making the joint strength greater than the base Ti.

Sahin [208] showed how tensile strength increased with either friction pressure or time to an optimum value of 4 s or 30 MPa, respectively, after which the strengths dropped off with continued pressure or time which they attribute to an excess formation of FeAl₃ intermetallic layer for a stainless steel-Al couple. Li et al. [132] found stainless steel-Ti alloy strength to increase with increasing friction time up to 4 s, however they note a greater variation at shorter or longer periods where the larger variation at longer periods is attributed to a wider IMC layer.

Excessive time or temperature can lead to detrimental growth of a brittle IMC layer along the faying interface in dissimilar material joints. This layer certainly is of importance, but the joint strength can also be influenced by alloying by diffusion, mechanical mixing, and mechanical deformation of the base materials along the interface. The IMC layers achieved in friction welding are typically less than that for resistance spot welding though peak strengths are achieved with comparable IMC layer thicknesses in the range of 0.2–2.0 μm for Al-steel joints [10]. The Al-steel inertia welded samples from Taban et al. [239] exhibited a maximum IMC layer of only 250 nm consisting of FeAl, which is

accounted for by a combination of intimate contact and heavy deformation in the AA6061 overcoming the activation barrier for diffusion to preferentially form FeAl and the more common Fe₂Al₅. Because of the relatively thin IMC layer, fracture occurred through the highly plasticized aluminium adjacent to the joint interface.

It is important to know the interfacial temperatures since this defines the rate of IMC formation. Misirli et al. [160] used thermocouples to experimentally measure the Al-304 stainless steel interface temperatures, which they showed to peak after 4 s of frictional contact. Alves et al. [7] experimentally determined Al1050-304 stainless steel heating & cooling temperature distributions which enabled them to characterize the interfacial microstructures and relate this to process parameters.

Dissimilar material joints exhibit deformation and flash generation in the lower strength material. Uday et al. [255] showed greater deformation in the Al workpiece for Al-Al composite and Rotundo et al. [201] showed no mixing of the SiC reinforcing particles in an Al-AlSi composite joint. Deformation occurred mainly on the Ti6Al4V side of a Ti6Al4V/SUS321 joint [132] which is remarkable in that the room temperature yield strength of Ti6Al4V is much greater though it is the elevated yield strength properties which are of interest. Thus, the deformation on the Ti6Al4V side is attributed to a larger decrease of tensile yield strength with temperature in the Ti6Al4V versus the SUS321 material. Related work investigating the effect of pressure, i.e. heat generation and its effect upon deformation in a Ti-Cu joint was also attributed to the varied flow stress temperature dependency of the two materials [118].

Joint strengths are often limited by the formation of intermetallic layers along the faying interface as is the case for the maximum joint efficiency of only 90% for friction welded stainless steel-titanium joints [132]. Thus, what can be found in the literature is a body of work highlighting the expansion of friction welding via new alloy combinations or investigation of process parameter-microstructure-property relationship in order to effect either relative deformation or intermetallic formation. Ambroziak et al. [10] embodies this in a review of Al-steel friction welding with a special focus on austenitic stainless steels and how bond strength can be affected by: (i) changing the geometry of the bond surface, (ii) using an interlayer to change the resulting intermetallic structure, or (iii) heat treatment.

Ashfaq et al. [17] showed how faying surface design of the harder 304 stainless steel influenced the flow of A6061 at the interface. Efficient flow along the interface helped with expulsion of impurities and IMC resulting in a good bond. With less efficient flow there would be greater heat build-up leading to a deeper dynamically recrystallized zone in the 6061. In a comparison of two steels with varied C-contents welded to A5052, Ikeuchi et al. [107] correlated IMC layer thickness to the deformation zone in the steel which was almost independent of welding parameters, C content of the steel, and type of Al alloy. Based upon the severe localized deformation within the steel, they propose that small fragments of the steel surface are incorporated into the Al alloy and forming IMC compounds. Luo et al. [141] applied external current during friction welding of Ni-based superalloy-42CrMo steel couple which not only reduced the overall heating time, but created a wavy and rugged interfacial structure which promoted mechanical interlocking in addition to bonding.

As in resistance spot welding, one approach to alter the IMC is to introduce an interlayer. Kannan et al. [111] show an indirect effect by incorporating a Ag interlayer between 6061/Al₂O₃ and 304 stainless steel which was shown to reduce the amount of heat generated, and decrease both the particle fracture tendency and the softened zone width at the bond line. However, others introduce an interlayer to directly alter the resulting IMC. Muralimohan et al. [172] introduced an Al interlayer for stainless steel-Ti couple. AlTi or Al₃Ti IMC formed versus FeTi or Fe_xTi, IMC with fracture occurring along the Ti-AlTi interface. Muralimohan and Muthupandi [171] applied a Ni interlayer for stainless steel-Ti

couple and also showed fracture along the newly formed TiNi IMC. Cheepu et al. [52] also applied a Ni interlayer between stainless steel-Ti couple and achieved a joint strength of 242 MPa and 308 MPa with an interlayer thickness of 30 and 50 μm, respectively.

Other work has investigated joints where one of the materials is copper-based. Mitelea et al. [161] investigated 42CrMo4-C45 steel and Cu-Al joints. Bhamji et al. [32] characterized the interfacial microstructure of Cu-Al joints. Teker [242] charted out the process-microstructure-properties for a Cu-AlSi2205 couple. Wanjara et al. [275] investigated the process-microstructure relationship of Cu-Al joints and found the fraction and size of IMC much improved vs explosion welding. Wu et al. [283] as well as Wang et al. [273] investigated the process-microstructure-property of Cu-35CrMnSi steel couples. Luo et al. [142] characterized the interface of a brass (Cu-Zn)-steel couple while Kurt et al. [121] investigated a bronze (Cu-Sn)-steel process-microstructure-property relationship. Other examples of new methods for solid state friction joining of dissimilar materials are the Friction Lap Welding (FLW) process developed by Liu et al. [135] for joining of metal and plastic materials.

2.4.4. Ultrasonic welding

Ultrasonic welding was invented in the 1960s, a US patent [98] on "Sonic method of welding thermoplastic parts" was granted to R.S. Soloff and S.G. Linsley in 1965. Ultrasonic welding uses high frequency ultrasonic vibration applied to create a solid-state weld. It is commonly used for plastics, and for joining dissimilar materials (see Fig. 21).

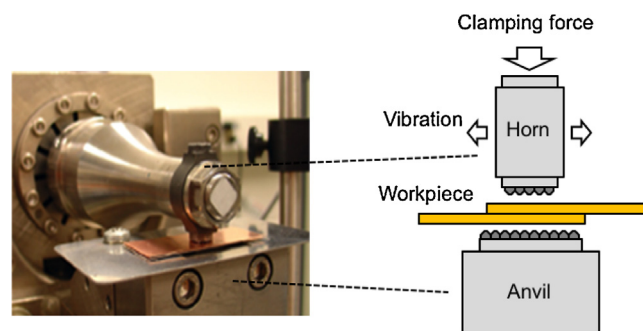


Fig. 21. Ultrasonic metal welding [129].

In ultrasonic metal welding, a horn and an anvil clamps the sheets to be joined together with pressure. The high frequency vibrations are applied along the direction of the joint being welded. The oscillating shears generated by the relative movements create a solid-state bond between metals [290]. This process overcomes the difficulties of multiple sheets of dissimilar materials by using its inherent advantages derived from the solid-state process characteristics [128,129]. In addition, unlike resistance welding and laser welding, the temperature in the ultrasonic welding process does not exceed the melting point of the metal workpiece, eliminating undesirable compounds, phases and metallurgical defects that commonly exist in most other fusion welds [11,117]. Due to these advantages, ultrasonic metal welding has been successfully applied to joining dissimilar materials in lithium-ion battery manufacturing. Wagner et al. [265] show an example of ultrasonic welding for joining of aluminium alloys and CFRPs creating a: "bonding zone with an intensive contact between the metallic surface and the load bearing carbon fibres".

2.4.5. Solid state welding by plastic deformation

Solid state welding by plastic deformation can be employed to join parts of sufficient ductility without the use of excessive heating, as done in fusion welding [83,84]. Metallurgical bonds can be achieved by large plastic deformation and breaking up oxide films, while mechanical joining should be performed without any

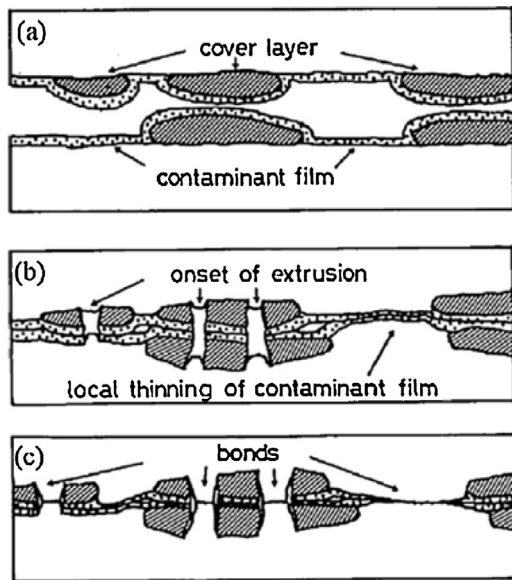


Fig. 22. Model for bonding mechanism in cold welding. (a) Scratch brushed surface, (b) extrusion of virgin material and (c) bonding [164].

thermal effects and focuses on oxide films, although interlocking and interfacial pressure should be used [164]. Cold welding or cold pressure welding is well-known as a process performed at the ambient temperature. This process can be used to join dissimilar materials such as Al-Ti, Al-Fe, Al-Cu and other material that is difficult to join by fusion welding [164]. The faying surfaces should be prepared before the welding to increase the bond strength. The welding must be performed shortly after preparation [164,295] (see Fig. 22).

Three main groups of cleaning treatment exists [164]: chemical cleaning, mechanical cleaning and initiation of brittle cover layer. Scratch brushing is one of the most important cleaning treatments. Mori et al. [164] emphasized that scratch brushing is the most appropriate cleaning procedure for such metal combinations as aluminium with copper and aluminium with mild steel. Cold welding is characterized by the following joining processes [164]: rolling, joining sheets of Al-Cu, Ni-stainless steel, steel-Cu, Al-stainless steel and others. Indentation and extrusion; mostly used in nuclear power and space technology by joining two-layer or three-layer tubes made of dissimilar materials, e.g. Al with Ti, Al with stainless steel and metals with ceramics [264].

2.5. Hybrid joining processes

2.5.1. Rivet-weld hybrid joining

Rivet-weld is a hybrid joining process that combines the strengths of self-piercing riveting and resistance welding for joining dissimilar materials, such as aluminium to steels [97]. Fig. 23 illustrates the concept of this technology. The associated process steps of rivet-weld is described below:

- (1) A weldable rivet is driven to pierce through a top sheet with the aid of a punch.

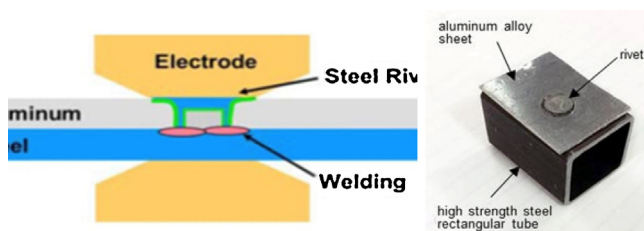


Fig. 23. Rivet-weld hybrid joining.

- (2) Upon contact of the rivet with a bottom sheet, a current is turned on. The resistance heat from the current flow causes local heating, which melts the rivet and the bottom sheet.
- (3) Upon cooling, a joint is formed linking the top sheet and the bottom sheet.

Rivet-weld bypasses the weaknesses of resistance welding and SPR in joining dissimilar materials, and keep the advantage of easy incorporation within the predominant Resistance Spot Welding (RSW) based assembly line infrastructure.

2.5.2. Friction riveting and friction spot welding process

Friction Riveting Process (FricRiveting) [8] and the Friction Spot Welding/Joining (FSPW/J) process [80], where invented with the objective of overcoming or attenuating the inherent limitations of the existing polymer-metal joining methods. The friction riveting process consists of rotating a metal rivet at high speeds and applying axial pressure as it is inserted into a polymer. This creates frictional heat from the rivet and melts a polymeric layer around the tip of the rotating rivet during the plunge stage.

During the heating the rivet tip temperature increases, as the thermal conductivity of the polymer is poor. As the rotation rate decelerates, the temperature in the polymer drops, which then increases the axial load on the plasticized rivet tip. This causes it to deform and increase its diameter into a new parabolic shape which acts to anchor the rivet into the polymer upon cooling to room temperature [36]. Refer to Fig. 24 for a process schematic. A good overview of the process can be found at [9] and a computational model to predict the mechanical performance of the FricRivet joint can be found at [37]. The process was demonstrated for a titanium rivet into a woven glass fibre reinforced polyetherimide (PEI) laminate considered for bridge construction by Blaga et al. [35].

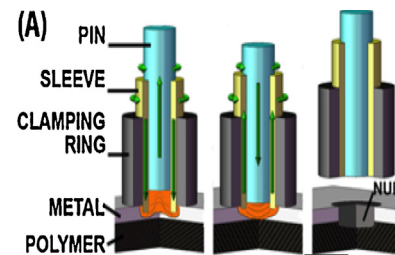


Fig. 24. FricRiveting Process

2.5.3. Injection over-moulding

Thermoplastic polymer-metal structures are more difficult to join by traditional joining methods, mostly due to their strong dissimilar physical-chemical features. One way to join thermoplastic polymer to metals is by in-mould assembly (IMA), also called injection over-moulding. The joining effect will typically be a combination of mechanical interlocking through the flow of the polymer, and the adhesive effect of the polymer wetting the metal surface. The metal part can for example have stamped or punched holes and the polymer melt can flow through or in the hole, refer to Fig. 25 for example. Grujicic et al. [85] discussed different approaches for polymer-metal joining with (micro-scale)

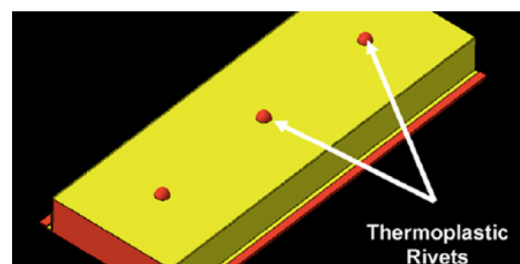


Fig. 25. Polymer-metal injection over-moulding joining for automotive load-bearing component [85].

mechanical interlocking, surface pre-coating and chemical modifications to the thermoplastics for enhanced adhesion.

3. Testing, inspection and modelling of dissimilar joints and hybrid structures

Testing, inspection and modelling goes hand-in-hand in modern product development. It is often necessary to combine different models and numerical approaches as well as different tests and inspection methods. Selection of the friction model can be crucial for a good model of joints.

3.1. Testing of joints and hybrid structures

The testing of structural components follows a hierarchical test regime: Testing of materials, geometries, demonstrator tests, and full scale testing. Two groups of test methodologies can be identified: procedural and demonstrator tests.

Procedural tests are generic and are used for characterization of the intrinsic mechanical properties of a particular joint type. Numerical models can improve test designs and the evaluation of results. Examples found in literature include; (i) laser assisted tape consolidation of thermoplastics [31], (ii) friction stir welding of dissimilar materials [88,126], (iii) mechanical connections [47,95], and (iv) adhesive connections [134,196].

Demonstrator tests are used to realize benchmark tests, where the quality of the methodologies is evaluated on more complex components closer to the physical structure. These components can feature several connection types and are submitted to realistic loading scenarios, e.g. low velocity impact. Several examples of polymer-metal hybrid structures are available in the literature [74,112].

3.2. Inspection methods

Generic joint inspection methods can be divided into two main categories: non-destructive (NDT) and destructive. The NDT tests include tests such as Liquid Penetrant, Electric Current, Eddy Current, Microwave, Ultrasonic, Acoustic Emission, Radiography and X-ray Computed Tomography. Destructive testing includes Hardness, Lap/Peel/Cross-Tension testing, Impact toughness, Microstructural and Fractography analysis. Adding to this are elements such as the joining process parameters, (joint) geometry, and surface morphology [261].

State-of-the-art inspection-technology useful for dissimilar joints are: X-ray Photoelectron Spectroscopy (XPS), Transmission Electron Microscopy (TEM), Scanning Transmission Electron Microscope (STEM), Scanning Electron Microscope (SEM) and Medium Energy Ion Scattering (MEIS) [94,229,261,282]. SEM can be useful to investigate the morphology of surface and crack patterns [229,261] as well as analysing the microstructure and thickness of IMC [293]. XPS can be used to investigate characteristics of bonding in the metal-polymer interface [94].

The behaviour of the binding interface was explored by Ho et al. [94] via microstructural and morphological analyses performed by transmission electron microscopy, and interface composition performed by MEIS. Zhang et al. [293] used EDX analysis to determine phases of the intermetallic compound layer after welding-brazing of aluminium with steel. Qi and Song [187] used SEM, EDS and XRD to investigate fracture surface and phases generated at the interface of the Mg alloy/Ni interlayer [187]. Development in ultrasonic inspection methods has been claimed in the literature to deliver significantly improved inspection performance, but the size, position and impact of test defects are difficult to assess [66,222].

3.3. Modelling of joining of dissimilar materials

Numerical methods have been widely developed in the last decades to predict the non-linear behaviour of complex structures

with accuracy, thus reducing the costs of expensive prototyping. Testing, inspection, modelling and simulation are mutually important to understand and predict the performance of the processes and the product. FEM methods enable modelling of large structures and access to local behaviour with good accuracy. Specific material data exist for most engineering materials [220]. When modelling hybrid structures, the modelling of connections is a challenge. This can be solved by simplification of the model representing the connections [119,63].

Modelling can be focused on the joining process itself, the performance of the finished joint/structure or both. Process modelling predicts the effect of process parameters on the joint formation, and performance modelling predicts the joint behaviour in the use phase. Usually there will be no strict division between the two, since joint performance usually is very dependent on the joining process.

3.3.1. Examples of process modelling

Development of numerical models to simulate joining processes to obtain optimal process parameters has been actively investigated during the last 20 years. In gas metal arc welding, higher quality joints and process stability can be achieved by simulation of metal droplet shape and formation in the metal transfer process [73,266]. According to Wang et al. [266], methods developed earlier consider effects of surface tension, gravity and electromagnetic force, but heat transfer and phase change effects are not taken into consideration. Examples of such methods are: (i) volume of fluid (VOF) and enthalpy methods [56], (ii) one-dimensional analysis [51], (iii) the pinch instability theory, and (iv) static force balance theory [73,266]. Based on these approaches, non-isothermal models were developed, providing an improved description of the metal transfer process [73]. Wang et al. [266] developed a new numerical model based on such approaches as "the enthalpy, effective-viscosity and VOF methods". This model allows simulating heat transfer process and phase changes, which is new compared to the earlier proposed models. Tomashchuk et al. [247] endeavoured in his research to solve the problems with the brittleness in the connection area of laser beam welding. Their multiphysical FE model, one-dimensional diffusion model and two-dimensional model based on the heat transfer, fluid flow and level set methods (provides prediction of composition and morphology of melted zone) are executed in the COMSOL Multiphysics software.

Another example is associated with the thermal modelling of friction welding process. A one-dimensional finite difference numerical model was developed and friction heat generation and temperature change as well as material deformation was modelled and evaluated [214]. Sahin et al. modelled FSW [205], and the relation between process parameters such as speed rotation, weld duration, friction load and their impact on mechanical properties (tensile strength, yield strength, hardness). They used a combination of Finite Element Methods (FEM) at two-dimensional heat-conduction model and a heat transfer model.

Zimmerman et al. [300] investigated friction welding thermo-mechanical parameters and geometry prediction through FEM simulations. Buffa et al. [40] showed how FEM modelling can predict optimum welding process parameters (see Fig. 26), and

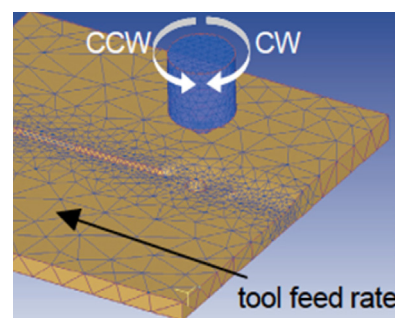


Fig. 26. Modelling of FSW by Buffa et al. [40].

Trimble et al. [250] combined FEM modelling and process monitoring of force and temperature to develop a 3D model capable of predicting tool forces.

Wang et al. [272] combined a wide spectrum of existing methodologies for studying the joint strength of PET and stainless steel fabricated by the laser transmission joining process. Thus, to determine the joint quality, the three main joining parameters laser power, stand-off-distance and joining speed were considered.

An other variation of using FEM are presented by Liao et al. [134]. The calculations are based on the Cowper-Symonds constitutive model, which takes into account the strain rate dependency. This is illustrated in Fig. 27. Hu et al. [101] simulated the welding process for joining stainless steel and nickel by a three-dimensional heat and mass model. The research is focused on the prediction of thermal stress, strain field, structure distortion, deformation, and microstructure. They used the Fourier heat conduction model for evaluation [101].

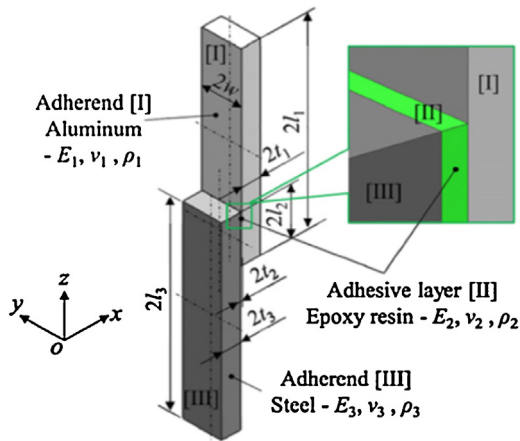


Fig. 27. Model and designations of dimensions for the FEM calculations for single-lap adhesive joint (aluminium-steel) [134].

Optimization of parameters for welding of immiscible materials was studied by Tomashchuk et al. This is possible to do by multi-physical modelling which allows one to analysis of the influence of operational parameters and material properties on joint morphology. Fluid flow, mass and heat transfer, weld speed and position of heat source where evaluated [248]. Chakraborty and Chakraborty [50] have shown how Reynolds Averaged Navier Stokes (RANS) is useful for simulations of turbulent molten pool convection in laser welding (Cu-Ni welding).

3.3.2. Modelling of adhesive and polymer joining

There are two ways of modelling adhesive connections in FEA. The first approach is computationally expensive, but enables more comprehensive knowledge on the deformation mechanisms in the joints. The models are able to reproduce and predict with accuracy the wide variety of large strain behaviour developing during the deformation in joints and polymer layers [38,68]. It is also able to capture the volume changes arising from the growth of cavities within materials and which may lead to ductile fracture of polymer joints. The final fracture mechanisms are still unclear, more specifically the rate sensitivity and temperature effect on fracture. Further research is needed on this topic. The effect of ageing, which will lead to progressive degradation of mechanical properties of the adhesive joint, is also an important area of research [130].

A modelling method that could be more suited for industrial application is the cohesive zone method (CZM) [5]. The CZM is developed in the area of fracture mechanics where the cohesive zone is at the tip of the fracture. Several authors have investigated the use of CZM for adhesive joints. The interface behaviour, including the damage onset and crack propagation, can be modelled using this approach. Strength prediction of adhesive

joints using CZM is described by Campilho [46], used as add-in to Finite Element (FE) analyses. An optimization of the cohesive model has been suggested by Cuvilliez et al. [61].

3.4. Modelling and testing: Industrial case from aerospace industry

Kapidžić et al. [112] describe an industrial case with testing, inspection and modelling. They studied the performance of a Al-CFRP hybrid wingbox structure and the performance of different solutions in case of a battle damage. Given the results from load distribution analysis, FEM analysis and physical testing, the authors could demonstrate performance parameters such as the best combination of resilience against battle damage and low weight. Concept 1 in Fig. 28 gave the best results and was chosen for further studies (Fig. 29 and Fig. 30).

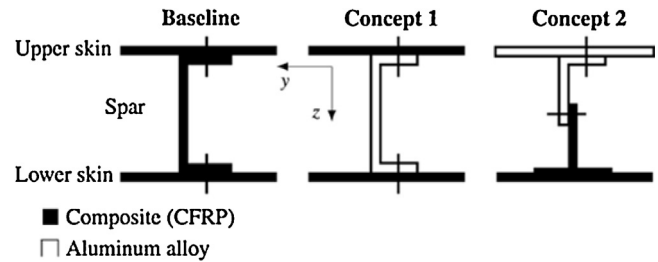


Fig. 28. Alternative hybrid structures [112].

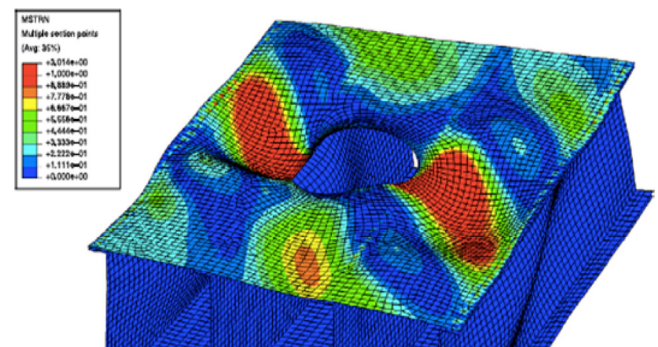


Fig. 29. FEM analysis of structure with battle damage [112].

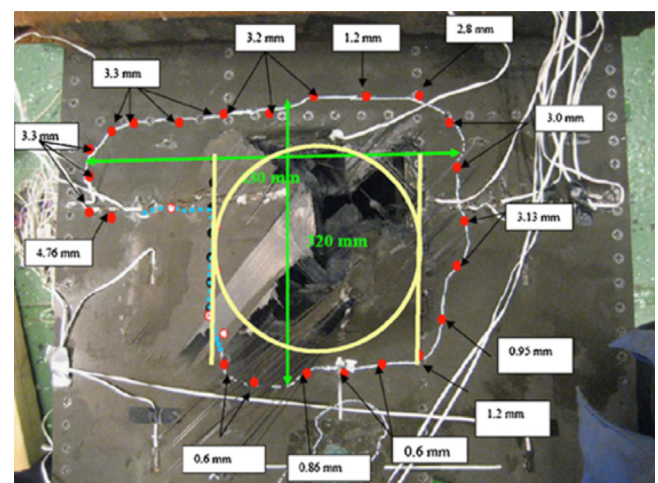


Fig. 30. Test specimen with battle damage [112].

4. Selection of joining methods for dissimilar materials

Selection of a joining process for dissimilar materials is a more complicated task than for similar materials because of different chemical and physical characteristics. Messler [149] classified dissimilar material according to "logic combinations" and the

potential difficulty of succeeding with a joint. Table 2 is produced by the authors, partly based on Messler and partly from the literature studied in this paper. The table lists preferred joining processes in descending order.

This table is a rough indication of the most common solutions. Other processes do exist and the preferred options are not necessarily the best choice for all cases. As the table shows, metals can for example be joined to ceramics (on macroscopic level) by: Brazing, Adhesives, Mechanical joining or Non-fusion welding, where Brazing is the most preferred. Fusion welding of ceramics and metals is rare, although welding of Al_3O_2 to W and Mo has been reported. Solid state (non-fusion) welding is more common, where bonding is created through diffusion of atoms between the two materials. Usually the joint is pressurized and heated to near the melting point of the metal. Messler [149] lists a large number of ceramic-metal combinations successfully diffusion welded. Indirect bonding using an intermediate bonding material is also common; the processes are usually Brazing or Soldering.

The selection of material, product design and joining method and process is a complex, interlinked task. Suggestions for systematic process selections exist in the literature [14,70,127,140,216] and books [13,234,235]. Decision support software exists [127], for example based on the PRIMA selection matrix [234,235] and process selection matrix [13] where columns correspond to selection criteria (joining conditions) and rows correspond to types of materials. It should be noted that information about dissimilar materials is not covered fully. CETIM has developed their own software with implementation matrices organized as a database [127]. This software works with the principle of excluding processes that don't respond to the selection criteria and requirements. Furthermore, the product and process development team must consider the pros and cons of the different joining methods. Some of these are discussed in Section 2 in this paper. From a generic standpoint, the authors of this paper wish to emphasise the following criteria for selecting a joining method:

- **Design of the joint:** The joint can be designed to suit a specific joining method, in other cases it is vice versa. This can be described from perspectives like mechanical design, product requirements, and minimum cost [140]. Maropoulos and Crookall [145] made an aggregated model of process and product for welding, with rapid conversion from product design to process and equipment requirements. Esawi and Ashby [70], Shercliff and Lovatt [216], Ashby et al. [14], Lovatt and Shercliff [140], Swift and Booker [234], and LeBacq et al. [127] are authors who emphasised the design of joint for a successful joining. Product design, material selection and the manufacturing processes are decisive for the mechanical properties of the product. Groche et al. [82] describes a method for manufacturing-induced properties in the product design phase. They describe an algorithm-based approach with optimization potentials. Product requirements include categories such as size, modes of loading [13], "geometry of the joint and functions required from the joint" [127]. The geometrical tolerance specifications of the parts to be joined as well as the process itself can be a challenge, especially for thermal joining with distortion problems. Söderberg et al. [237] describe a method for simulating geometrical variation in non-rigid assemblies.
- **Material selection and galvanic corrosion considerations:** The selection of materials is essential for the joining process [14,234,235] and the chemical and physical material characteristics are selection criteria in product development decision-making processes. [13,14,70,127,234,235,243]. Galvanic compatibility of the materials must be taken into account. This type of corrosion mechanism can be minimized by selecting combinations of metals that are close together in the galvanic series, by electrical insulation, and/or by application of coatings on the more noble material to reduce the cathode/anode area ratio. Compromises are generally required when designing a hybrid structure such as coating or intermediate non-corrosive

layers. FEM can provide an effective predictive tool for geometrical effects. Useful information on the rate of galvanic corrosion can further be obtained by electrochemical polarization.

- **Joining process conditions:** The joining process conditions will limit the possible joining processes for a selected hybrid structure. Temperatures, degree of precision required for the joint, position of processing, service of environment, roughness of materials, assembly place, pre- and post processes, robustness, etc. can only be applied to material and structures able to comply with the process requirements [13,14,70,127,234,235,243]. Söderberg et al. [238] describe a method for simulations of the influence from the variation in spot weld positioning on geometrical variation on the finished structure.
- **Health, environment and safety (HES):** Some joining processes might induce health and safety issues for operators; harmful chemicals, gas fumes, thermal or mechanical injuries, must be considered when choosing joining processes. Troughton [251] paid attention to the importance of health monitoring during the laser welding processes. Doraiswamy et al. [67] stressed the importance of using synthetic adhesives such as solvents and monomers applied in automotive and aerospace industries. They describe the increasing concerns around health and environmental issues due to smog and atmospheric ozone depletion caused by synthetic adhesives.
- **Flexible automation and Design for "X" (DFx):** The ability to automate the process can be necessary due to HES and cost issues. Michalos et al. [151] describe a number of important factors for future automotive assembly lines. Flexibility and adaptability, responsiveness, fixtureless assembly, and human-robot collaboration are mentioned. The ability to automate the process is often influenced by the product design. Methodologies such as Design for "X" should be included in the product design phase [140].
- **Sustainability and Life Cycle Engineering:** The increased focus on sustainability raises demands on the joining processes (Beginning of Life), but also the expected sustainability losses during use-phase (Middle of Life) and the End of Life. Possibilities for repair, reuse, recycling and disassembly should be considered when choosing the joining method [140]. Sustainability considerations need, however, a holistic approach. Structural integrity and lightweight can be more important than ease of disassembly for the optimum process selection. Applications of Life Cycle Engineering tools is advisable.
- **Profitability:** All steps above include, in some sense, economic considerations from different perspectives. The overall profitability is of course one of the important decision criteria for the joining method [127,140,234,235].

4.1. Examples from automotive industry

Michalos et al. [151] pointed out that "Implementation of advanced joining technologies offering improved quality, productivity and safety", where light weighting is one of the major tasks for automotive product design. Except for air-drag losses, the energy losses that must be overcome by the propulsion system, i.e., fuel consumption, are proportional to the vehicle mass [45]. Furthermore, reducing mass in a portion of the vehicle leads to further mass reduction opportunities in other part of the vehicle, giving rise to the term mass de-compounding [262], which further reinforces the value of light weighting. This is now driven by the upcoming legislation targeting improved fuel economy [64]. To address the pressing issue of mass reduction, the automotive industry is moving towards a strategy of applying the right material at the right place leading to mixed material solutions such as the Mercedes S-Class [150] which uses plastics, three forms of aluminium and five grades of steel in the BIW construction [41]. The 2014 Cadillac CTS [212] contains press-hardened steel side impact bars in an aluminium door construction. Further penetration of aluminium stampings will be enabled by tailor

welded blanks manufactured by friction stir welding [99]. Significant strides are being made in advanced HSS with greater formability towards targets of 1 GPa and 30% elongation. Magnesium is typically used where multiple components can be integrated [204]. The issue of galvanic corrosion has, however, been a limiting factor in broad application of magnesium alloys. CFRP materials offer the greatest potential for mass savings. New technologies are enabling higher volume applications, but the cost targets and a competitive CO₂ emission reduction have not yet been achieved.

5. Research challenges for future joining of dissimilar materials

5.1. Industrial challenges and opportunities

The EU Manufacture Sub-platform on Joining [6] has prepared a Strategic Research Agenda (SRA) with focus on industrial drivers, challenges and opportunities relevant for joining divided into different sectors. Many of these challenges relate to joining of dissimilar materials. For the *Automotive sector* dissimilar/hybrid materials joining of aluminium, steel, high strength steel, composites, and thermoplastics are identified in the SRA. Low electrical resistivity joints are needed for electric cars and hydrogen powered vehicles need joints suitable for high-pressure hydrogen handling. In the *power production sector* joining of composites to metal for turbine blades, joining of lightweight structures of metals and composites for solar panels, joining technologies for fuel cell components and joining of ceramics are identified. *Aerospace sector* needs to innovate on joining of polymer composites to metals and joining of high temperature materials. *The construction and transportation sectors* have challenges regarding joining of dissimilar/hybrid materials including aluminium, steel, high strength steel, polymer fibre composites and thermoplastics. *Electronics and Nano technology* focus on circuit boards and joining processes like miniaturized soldering and bonding and joining of copper to aluminium and metals to polymers.

The *Medical sector* needs to solve problems in joining of higher performance materials for orthopaedics, and dissimilar polymer joining for diagnostic equipment. Cardio-vascular medical devices need innovations in thin section joining of mixed materials for catheters and joining of advanced materials such as shape memory and super-elastic metals. Other challenges listed in the SRA include joining of foils to polymer products, fabrication of electronic packages into implantable metal products (laser joining, ceramic sealing and prototype design), joining of super-elastic alloys to steel, joining of super-elastic alloys to polymer products. Finally, for the *oil and gas sector* there is a need for innovation in the joining of steel of different grades and thicknesses and joining of composites and metals (pipes, fittings flanges).

5.2. Future research challenges identified

There are of course a large number of research challenges in this field. Novel processes are being developed, and there is still a lot to be studied to reach a more comprehensive understanding of existing processes. There is a constant hunt for improvement in product and process properties: ductility, strength, robustness, performance, productivity, health and security, sustainability, life expectancy and extension, flexible automation etc. The authors wish to identify some research areas common to several of the joining processes described. This is an indication of needed future basic research and development of enabling technology useful to achieve the desired product and process innovations.

5.2.1. Increased understanding of basic bonding mechanisms

A deeper understanding of the basic bonding mechanisms is needed for many dissimilar joining processes. This understanding

will provide necessary input for calibration of FEM simulations and other numerical models. New test methodologies must be developed in order to assess and evaluate the basic bonding properties and the quality of both existing and newly developed technologies. The methodologies should also be a validation and benchmark of the numerical models. The output will be a valuable input for evaluation of properties and allows early feedback in the innovation process.

5.2.2. Identify critical process, material miss-match situations and/or main mechanisms for failure

The research community must gain more knowledge on failure mechanisms. This is vital in the design phase in order to avoid structural failures. The research will be a combination of microstructural mechanical characterisation and mechanical testing, advanced electron microscopy and numerical modelling. Typical failures can be due to: (i) design choice: thermal expansion, galvanic contact, stress corrosion, etc. (ii) processing failures: formability gradients, heat capacity differences, bonding mechanisms, etc., and (iii) exposure in the use phase: thermal & mechanical load history, degradation, corrosion and ageing.

5.2.3. Bridge the gap between the modelling scales

There is a need to bridge the gap between modelling scales from atomistic level to macro level, from microstructure to continuum mechanics and process modelling. The models should provide input to optimization, emulation and simulation tools for the joining processes and the product/joint. Hand-in-hand with the improved modelling, there must be improved tests- and inspection methods for calibration and validation of the models. Local-micromechanics approaches to understand fundamental physical mechanisms serve as input to macroscopic models. Future research is needed in the following areas: (i) damage development and crack propagation in adhesive layers, (ii) fracture of mechanical connections, (iii) Interface properties with atomistic models, (iv) process effect on the connection behaviour and (v) Ab initio based atomistic interface models to calculate bonding energies used as boundary conditions in continuum based models, making larger scale simulations possible [87,180].

5.2.4. Sensing in dissimilar joining processes

Sensor-based process monitoring and control and automated quality inspection is widely used in manufacturing and sensor data from joining processes will be an important part of in the cyber-physical system of future manufacturing. Future research is needed to utilise the potential of novel sensors to meet the challenges of joining of dissimilar materials.

5.3. Standardisation

There is a lack of standardisation in the field of testing and characterisation of dissimilar materials joints, and currently no generally agreed upon materials testing standard for dissimilar metal welds. The methods rely on test specimens that do not always sample the most vulnerable microstructures. Moreover, dissimilar materials can create problems for structural assessment because the stress fields have a significant mixed mode component and in addition to the mismatch between tensile plasticity properties of the different materials. Both of these affect the constraints acting on a crack and its tendency to propagate. Whereas fracture mechanics procedures are now well established for orthogonal stress fields and homogeneous materials, there is a lack of experimental data for current approaches applied in more complex situations. Furthermore, a quantitative description of the magnitude and distribution of residual stresses within a dissimilar metal weld on an industrial scale is lacking. The European Commission sponsored ADIMEW project made recommendations regarding the testing and data analysis methods to be applied when characterizing a dissimilar metal weld [72].

6. Conclusions

The trends of light weighting, higher performance and increased functionality are some of the drivers for multi-material, hybrid structures and the need for joining of dissimilar materials. Different material properties are utilized to achieve improvements not possible with a single material. This paper has reviewed selected joining processes suitable for the joining of dissimilar materials. Selection criteria, modelling and inspection/testing of joints have been discussed. There are, however still many challenges to be solved and need for further research. The authors wish by this paper to contribute to closer collaboration between the manufacturing research and joining research communities, and to raise the awareness of the importance of innovations in this area.

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